Mobile Communications

TCS 455

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Lecture 20

Office Hours:
BKD 3601-7
Tuesday 14:00-16:00
Thursday 9:30-11:30

Announcements

- Read
  - Chapter 9: 9.1 – 9.5
- No class on Jan 21 (This Thursday) – university game
- Class will resume on Feb 2
- HW5 is posted.
  - Due: Feb 5 (Friday after university game)

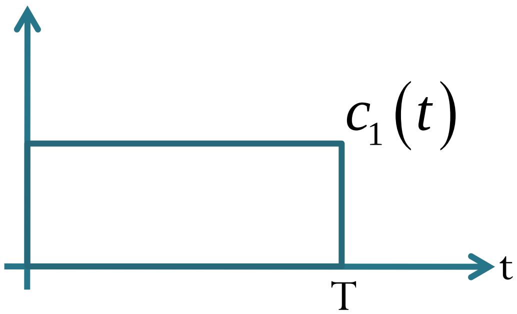
CDMA

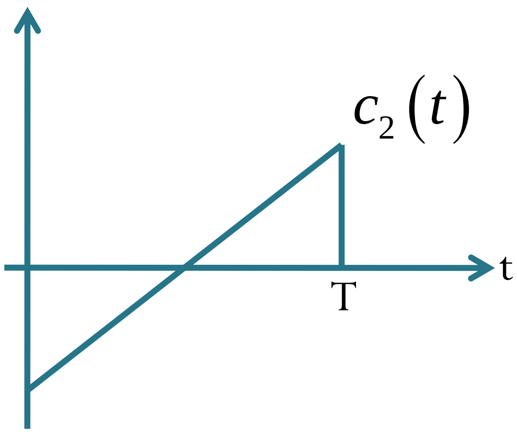
- One way to achieve SSMA
- May utilize Direct Sequence Spread Spectrum (DS/SS)
  - Direct sequence is not the only spread-spectrum signaling format suitable for CDMA
- All users use the same carrier frequency and may transmit simultaneously.
- Users are assigned different "**signature waveforms**" or "code" or "codeword" or "**spreading signal**"

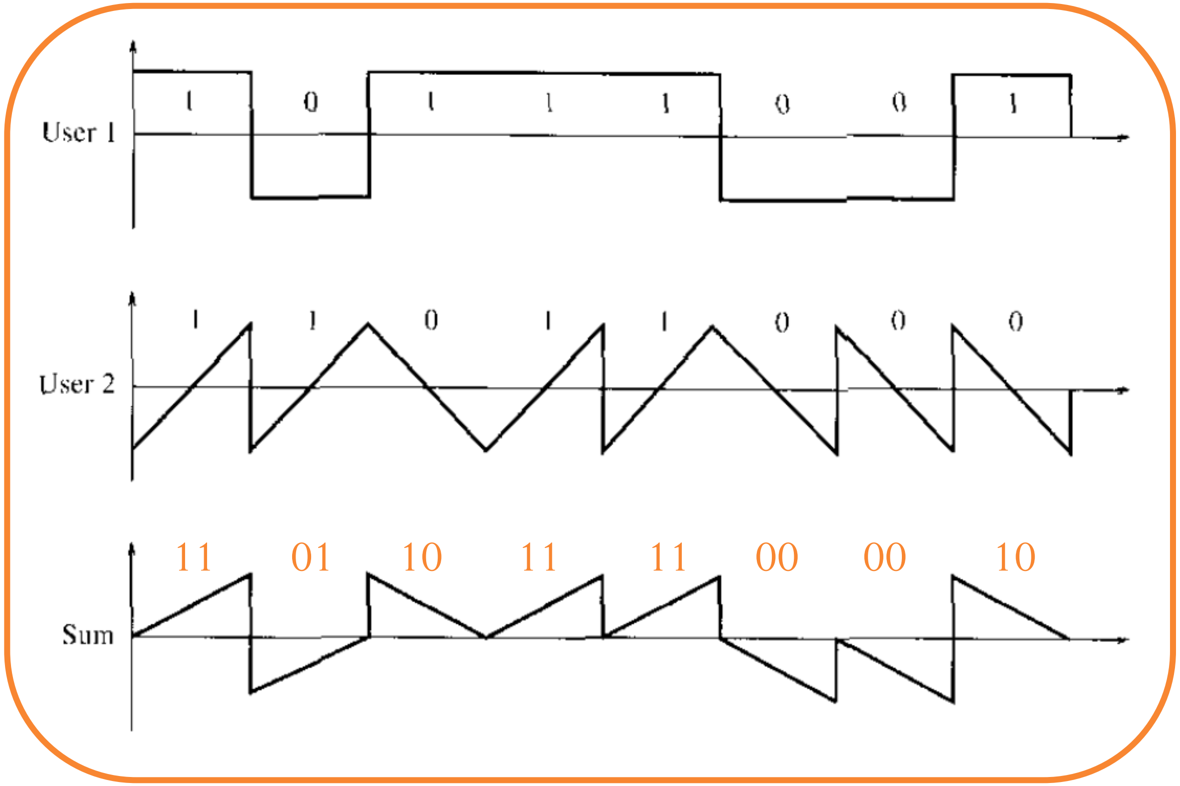
Not to be confused with error-correcting codes that add redundancy to combat channel noise and distortion

- The narrowband message signal is multiplied (modulated) by the **spreading signal** which has a very large bandwidth (orders of magnitudes greater than the data rate of the message).
- Each user's codeword is ***approximately orthogonal*** to all other codewords.
- Should not be confused with the mobile phone standards called cdmaOne (Qualcomm's IS-95) and CDMA2000 (Qualcomm's IS-2000) (which are often referred to as simply "CDMA")
  - These standards use CDMA as an underlying channel access method.

CDMA: Simplified Example (1)

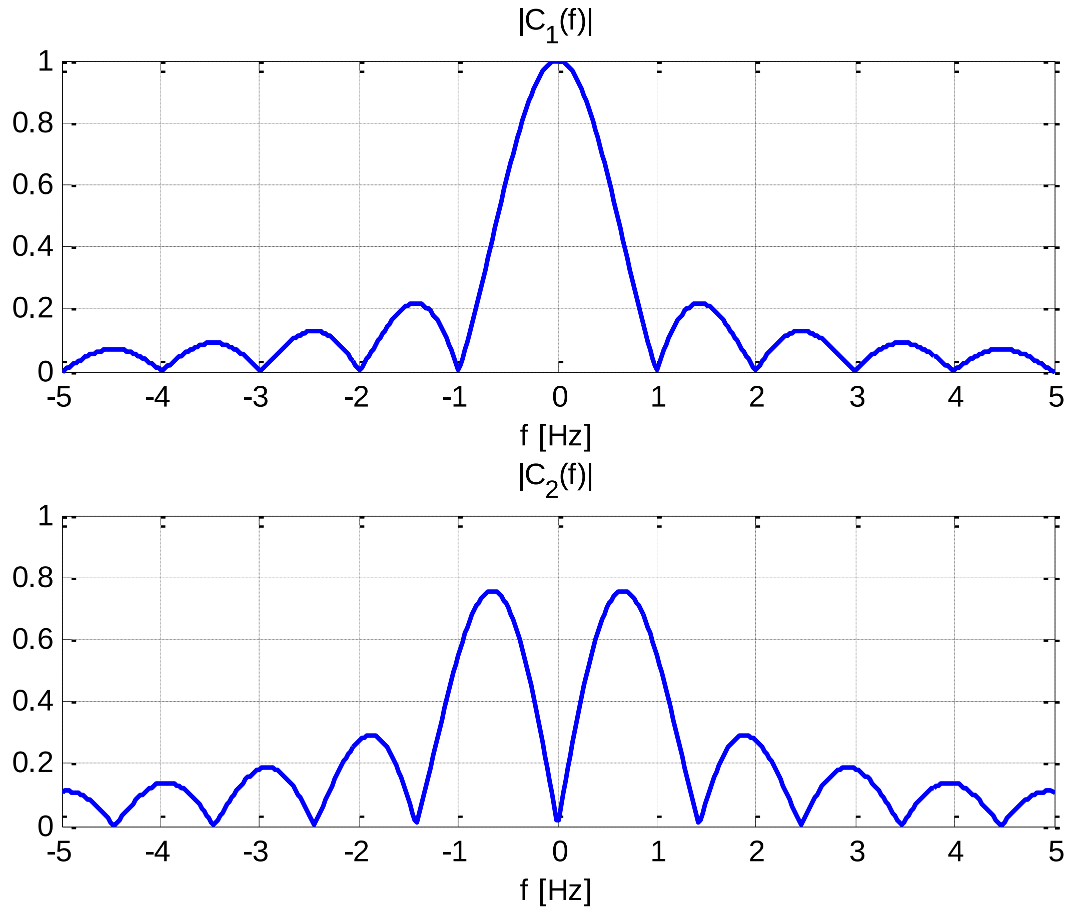






[Figure 1.6, Verdu, 1998]

CDMA: Simplified Example (1) – con’t



CDMA

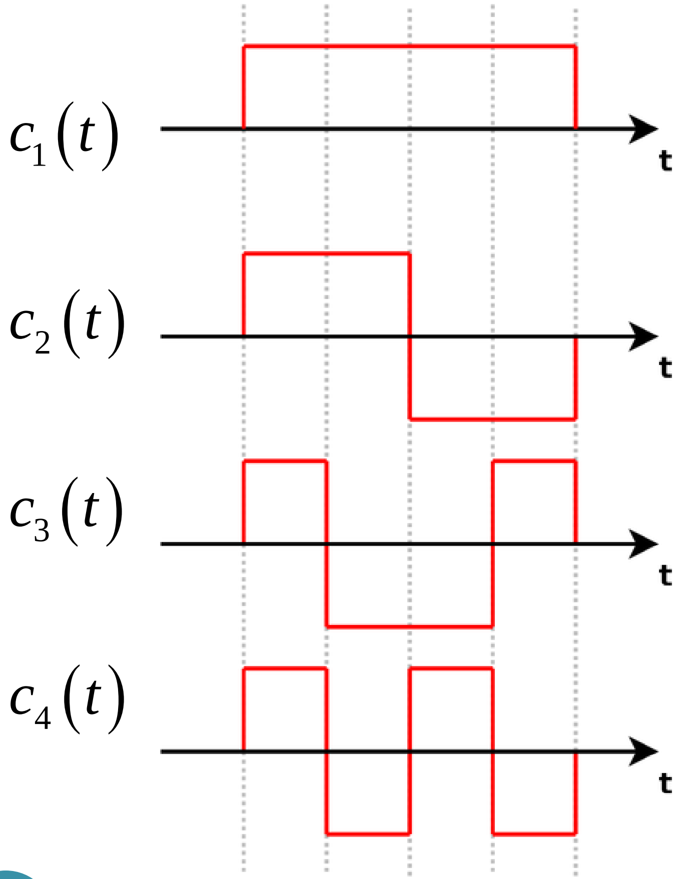
- Reception free from inter-channel interference is a consequence of the use of orthogonal signaling.
- This can be accomplished by signals that overlap both in time and in frequency.
- **Orthogonal (real-valued) signals**:

Inner product, Cross-correlation → $$\langle c_1, c_2 \rangle = \int_0^T c_1(t) c_2(t) dt = 0$$

- Special case: TDMA
  - The signature waveforms do not overlap in the time domain.

CDMA: Simplified Example (2)

- An example of four mutually orthogonal digital signals.



CDMA: DS/SS

- The receiver performs **a time correlation operation** to detect only the specific desired codeword.
- All other codewords appear as noise due to decorrelation.
- For detection of the message signal, the receiver needs to know the codeword used by the transmitter.
- **Each user operates independently with no knowledge of the other users**.
- Unlike TDMA or FDMA, CDMA has a **soft capacity limit**.
  - Increasing the number of users in a CDMA system raises the noise floor in a linear manner.
  - There is no absolute limit on the number of users in CDMA. Rather, the system performance gradually degrades for all users as the number of users is increased and improves as the number of users is decreased.

Analogy [Tanenbaum, 2003]

- An airport lounge with many pairs of people conversing.
- TDMA is comparable to all the people being in the middle of the room but taking turns speaking.
- FDMA is comparable to the people being in widely separated clumps, each clump holding its own conversation at the same time as, but still independent of, the others.
- CDMA is comparable to everybody being in the middle of the room talking at once, but with each pair in a different language.
  - The French-speaking couple just hones in on the French, rejecting everything that is not French as noise.
  - Thus, the key to CDMA is to be able to extract the desired signal while rejecting everything else as random noise.

Problem of CDMA

- The spreading sequences of different users are not exactly orthogonal
  - In a mobile environment, multipath receptions may contribute to the interference power for each mobile station.
- In the despreading of a particular code, non-zero contributions to the receiver decision statistic for a desired user arise from the transmissions of other users in the system.

CDMA: Near-Far Problem

- At first, CDMA did not appear to be suitable for mobile communication systems because of this problem.
- Occur when many mobile users share the same channel.
- In an uplink, the signals received from each user at the receiver travel through different channels. This gives rise to the near-far effect, where users that are close to the uplink receiver can cause a great deal of interference to user's farther away.
  - In general, the strongest received mobile signal will capture the demodulator at a base station.
- Stronger received signal levels raise the noise floor at the base station demodulators for the weaker signals, thereby decreasing the probability that weaker signals will be received.
- Fast **power control** mechanisms solve this problem.
  - Regulate the transmit power of individual terminals in a manner that received power levels are balanced at the base station.

Synchronous CDMA Model

- Bit epochs are aligned at the receiver
- Require
  - closed-loop timing control or
  - Providing the transmitters with access to a common clock (such as the Global Positioning System)

How many orthogonal signals?

- No signal can be both strictly time-limited and strictly band-limited.
- We adopt a softer definition of bandwidth and/or duration (e.g., the percentage of energy outside the band [-B, B] or outside the time interval [0, T] not exceeding a given bound ε.
- Q: How many mutually orthogonal signals with (approximate) duration T and (approximate) bandwidth B can be constructed?
- A: About 2TB
  - No explicit answer in terms of T, B, and ε is known.
  - Unless the product TB is small.
- A *K*-user orthogonal CDMA system employing antipodal modulation at the rate of R bits per second requires bandwidth approximately equal to

$$B = \frac{1}{2} RK$$

Walsh Functions [Walsh, 1923]

- Walsh codes are used in second- and third-generation cellular radio systems for providing channelization
- A set of Walsh functions can be ordered according to the number of zero crossing (sign changes)

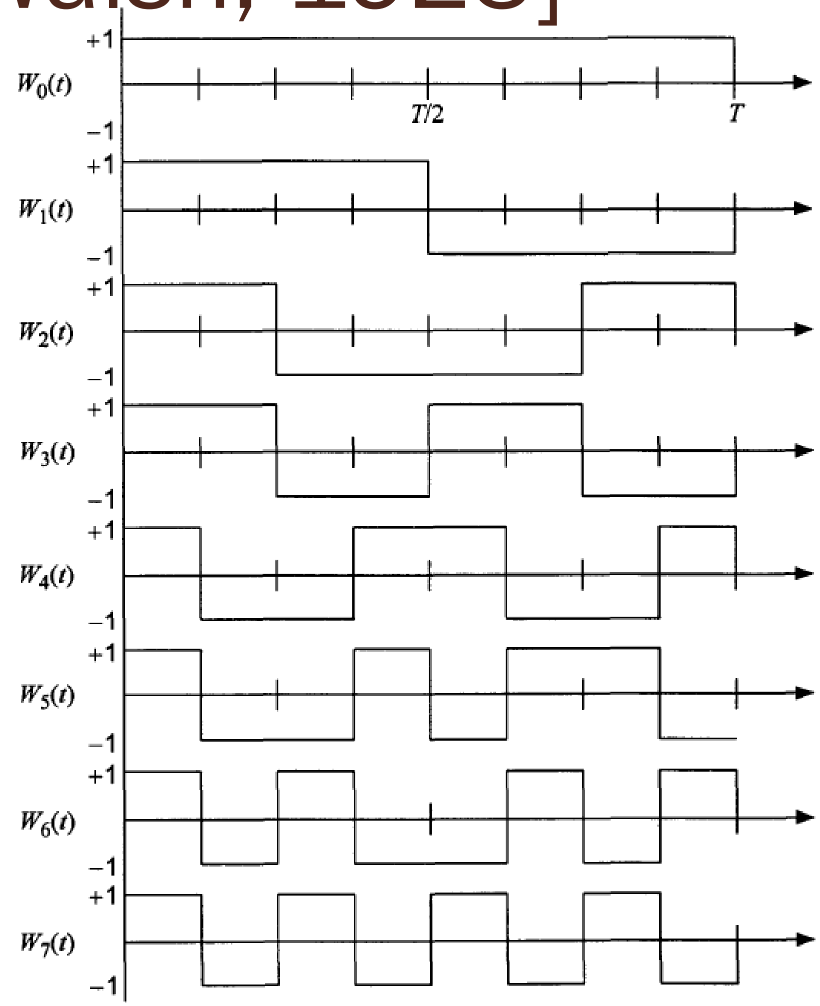


Figure 5.1 The Walsh functions of order 8.

[Lee and Miller, 1998, Fig. 5.1]

Walsh Functions (2)

We define the Walsh functions of order N as a set of N time functions, denoted $\{W_j(t); t \in (0, T), j = 0, 1, \ldots, N-1\}$, such that

- $W_j(t)$ takes on the values $\{+1, -1\}$ except at the jumps, where it takes the value zero.
- $W_j(0) = 1$ for all j.
- $W_j(t)$ has precisely j sign changes (zero crossings) in the interval $(0, T)$.
- $$\int_0^T W_j(t)\, W_k(t)\, dt = \begin{cases} 0, & \text{if } j \neq k \\ T, & \text{if } j = k \end{cases}$$ Orthogonality
- Each function $W_j(t)$ is either odd or even with respect to the midpoint of the interval.

Once we know how to generate these Walsh functions of any order N, we can use them in N-channel orthogonal multiplexing applications.

Walsh Sequences

Walsh sequences
$W_0 = 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0$
$W_1 = 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1$
$W_2 = 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0$
$W_3 = 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1$
$W_4 = 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0$
$W_5 = 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 1$
$W_6 = 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0$
$W_7 = 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1$
$W_8 = 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0$
$W_9 = 0\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1$
$W_{10} = 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 1\ 0\ 1\ 1\ 0$
$W_{11} = 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1$
$W_{12} = 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0$
$W_{13} = 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 1$
$W_{14} = 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0$
$W_{15} = 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1$

- The Walsh functions, expressed in terms of ± 1 values, form a group under the multiplication operation (multiplicative group).
- The Walsh sequences, expressed in terms of (0, 1) values, form a group under modulo-2 addition (additive group).
- Closure property:

$$W_i(t) \cdot W_j(t) = W_r(t)$$

$$W_i \oplus W_j = W_r$$

Walsh sequences of order 64

Table 5.2 Walsh functions of order 64 (indexed by zero crossings)

W_{0}	0000000000000000	0000000000000000	0000000000000000	0000000000000000
W_{1}	0000000000000000	0000000000000000	1111111111111111	1111111111111111
W_{2}	0000000000000000	1111111111111111	1111111111111111	0000000000000000
W_{3}	0000000000000000	1111111111111111	0000000000000000	1111111111111111
W_{4}	0000000011111111	1111111100000000	0000000011111111	1111111100000000
W_{5}	0000000011111111	1111111100000000	1111111100000000	0000000011111111
W_{6}	0000000011111111	0000000011111111	1111111100000000	1111111100000000
W_{7}	0000000011111111	0000000011111111	0000000011111111	0000000011111111
W_{8}	0000111111110000	0000111111110000	0000111111110000	0000111111110000
W_{9}	0000111111110000	0000111111110000	1111000000001111	1111000000001111
W_{10}	0000111111110000	1111000000001111	1111000000001111	0000111111110000
W_{11}	0000111111110000	1111000000001111	0000111111110000	1111000000001111
W_{12}	0000111100001111	1111000011110000	0000111100001111	1111000011110000
W_{13}	0000111100001111	1111000011110000	1111000011110000	0000111100001111
W_{14}	0000111100001111	0000111100001111	1111000011110000	1111000011110000
W_{15}	0000111100001111	0000111100001111	0000111100001111	0000111100001111
W_{16}	0011110000111100	0011110000111100	0011110000111100	0011110000111100
W_{17}	0011110000111100	0011110000111100	1100001111000011	1100001111000011
W_{18}	0011110000111100	1100001111000011	1100001111000011	0011110000111100
W_{19}	0011110000111100	1100001111000011	0011110000111100	1100001111000011
W_{20}	0011110011000011	1100001100111100	0011110011000011	1100001100111100
W_{21}	0011110011000011	1100001100111100	1100001100111100	0011110011000011
W_{22}	0011110011000011	0011110011000011	1100001100111100	1100001100111100
W_{23}	0011110011000011	0011110011000011	0011110011000011	0011110011000011
W_{24}	0011001111001100	0011001111001100	0011001111001100	0011001111001100
W_{25}	0011001111001100	0011001111001100	1100110000110011	1100110000110011
W_{26}	0011001111001100	1100110000110011	1100110000110011	0011001111001100
W_{27}	0011001111001100	1100110000110011	0011001111001100	1100110000110011
W_{28}	0011001100110011	1100110011001100	0011001100110011	1100110011001100
W_{29}	0011001100110011	1100110011001100	1100110011001100	0011001100110011
W_{30}	0011001100110011	0011001100110011	1100110011001100	1100110011001100
W_{31}	0011001100110011	0011001100110011	0011001100110011	0011001100110011
W_{32}	0110011001100110	0110011001100110	0110011001100110	0110011001100110
W_{33}	0110011001100110	0110011001100110	1001100110011001	1001100110011001
W_{34}	0110011001100110	1001100110011001	1001100110011001	0110011001100110
W_{35}	0110011001100110	1001100110011001	0110011001100110	1001100110011001
W_{36}	0110011010011001	1001100101100110	0110011010011001	1001100101100110
W_{37}	0110011010011001	1001100101100110	1001100101100110	0110011010011001
W_{38}	0110011010011001	0110011010011001	1001100101100110	1001100101100110
W_{39}	0110011010011001	0110011010011001	0110011010011001	0110011010011001
W_{40}	0110100110010110	0110100110010110	0110100110010110	0110100110010110
W_{41}	0110100110010110	0110100110010110	1001011001101001	1001011001101001
W_{43}	0110100110010110	1001011001101001	0110100110010110	1001011001101001
W_{44}	0110100101101001	1001011010010110	0110100101101001	1001011010010110
W_{45}	0110100101101001	1001011010010110	1001011010010110	0110100101101001
W_{46}	0110100101101001	0110100101101001	1001011010010110	1001011010010110
W_{47}	0110100101101001	0110100101101001	0110100101101001	0110100101101001
W_{48}	0101101001011010	0101101001011010	0101101001011010	0101101001011010
W_{49}	0101101001011010	0101101001011010	1010010110100101	1010010110100101
W_{50}	0101101001011010	1010010110100101	1010010110100101	0101101001011010
W_{51}	0101101001011010	1010010110100101	0101101001011010	1010010110100101
W_{52}	0101101010100101	1010010101011010	0101101010100101	1010010101011010
W_{53}	0101101010100101	1010010101011010	1010010101011010	0101101010100101
W_{54}	0101101010100101	0101101010100101	1010010101011010	1010010101011010
W_{55}	0101101010100101	0101101010100101	0101101010100101	0101101010100101
W_{56}	0101010110101010	0101010110101010	0101010110101010	0101010110101010
W_{57}	0101010110101010	0101010110101010	1010101001010101	1010101001010101
W_{58}	0101010110101010	1010101001010101	1010101001010101	0101010110101010
W_{59}	0101010110101010	1010101001010101	0101010110101010	1010101001010101
W_{60}	0101010101010101	1010101010101010	0101010101010101	1010101010101010
W_{61}	0101010101010101	1010101010101010	1010101010101010	0101010101010101
W_{62}	0101010101010101	0101010101010101	1010101010101010	1010101010101010
W_{63}	0101010101010101	0101010101010101	0101010101010101	0101010101010101

[Lee and Miller, 1998, Table 5.2]